



The FNAL Proton Complex and its Evolution for NuMI and mu2e

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Fermilab Wine and Cheese
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Brief Post MECA History

- January 2006: Peter Yamin & Jim Miller organized a meeting at BNL between Fermilab people & ex-MECO people interested in the possibility of a $\mu \rightarrow e$ conversion experiment at FNAL.
- We agreed to explore possible concepts for the required proton beam at Fermilab, & if things look promising, to arrange a follow-up meeting at Fermilab (meeting taking place now).
- Over the last few months the Fermilab "group" has met once every 2-3 weeks with lots of discussion enlightened by some modest work.
- We think we have arrived at an attractive concept, but its at an early stage (no engineering and many details needing attention).
- Along the way we have been encouraged at FNAL (by Directorate & PAC) to explore the possibilities.



Interested Fermilab Scientists

C. Ankenbrandt	D. Finley	D. Neuffer
D. Bogert	S. Geer*	M. Popovic
S. Brice	E. Gottschalk	E. Prebys*
D. Christian	M. Martens	R. Ray
F. DeJongh	D. McGinnis	H. White

15 Scientists

50% from Accelerator Division, 50% from Particle Physics Division

* Ad hoc steering group members



Stages

- Stage 1: The Proton Plan.
 - Booster aperture upgrades
 - Slip stacking in the Main Injector
- Stage 2: SNUMI 1
 - Slip Stacking in the Recycler
 - Main Injector "Load and Go"
 - Main Injector Cycle time reduces from 2.1 sec to 1.3 sec
- Stage 3: SNUMI 2
 - Proton momentum stacking in the Accumulator
 - Box Car stacking in the Recycler
 - Main Injector "Load and Go"



Booster Throughput Scenarios

- All the proton upgrades rely on increased Booster throughput

Parameter	Sept. 2005	Prot. Plan	SNUMI 1	SNUMI 2a	SNUMI 2b	
Booster Flux	6.4	13.5	13.1	22.6	25.1	$\times 10^{16}/\text{Hr}$
Collider Flux	1.1	1.5	0.0	0.0	0.0	$\times 10^{16}/\text{Hr}$
NUMI Flux	3.2	7.5	13.1	22.6	20.5	$\times 10^{16}/\text{Hr}$
NUMI Beam Power	162	372	648	1181	1073	kW
8 GeV Flux	2.1	4.5	0.0	0.0	4.6	$\times 10^{16}/\text{Hr}$

Parameter	Sept. 2005	Prot. Plan	SNUMI 1	SNUMI 2a	SNUMI 2b	
Collider Final Intensity	6.9	8	0	0	0	$\times 10^{12}$
NUMI Final Intensity	22	40	45	82	82	$\times 10^{12}$
MI Cycle Time	2.60	2.07	1.33	1.33	1.47	Sec
Collider Batches	2	2	0	0	0	
NUMI Batches	5	9	12	18	18	



Multi-stage Proton Accumulator Motivation

- Slip stacking multiple Booster batches in either the Main Injector or the Recycler is the central concept for proton fluxes up to 14×10^{16} protons/hour
 - Longitudinal stacking at 8 GeV reduces the peak intensity requirement in the Booster
 - Results in a smaller required aperture for the Booster
 - Smaller space charge tune shift
 - Reduced requirements on acceleration efficiency
- Above 14×10^{16} protons/hour, the number of batches stacked into the Recycler can not be increased further by slip stacking because of the rather severe amount of emittance dilution that is fundamental to the slip stacking process.
- Momentum Stacking has much smaller longitudinal emittance dilution than slip stacking and can be used in place of slip stacking to achieve proton fluxes greater than 14×10^{16}



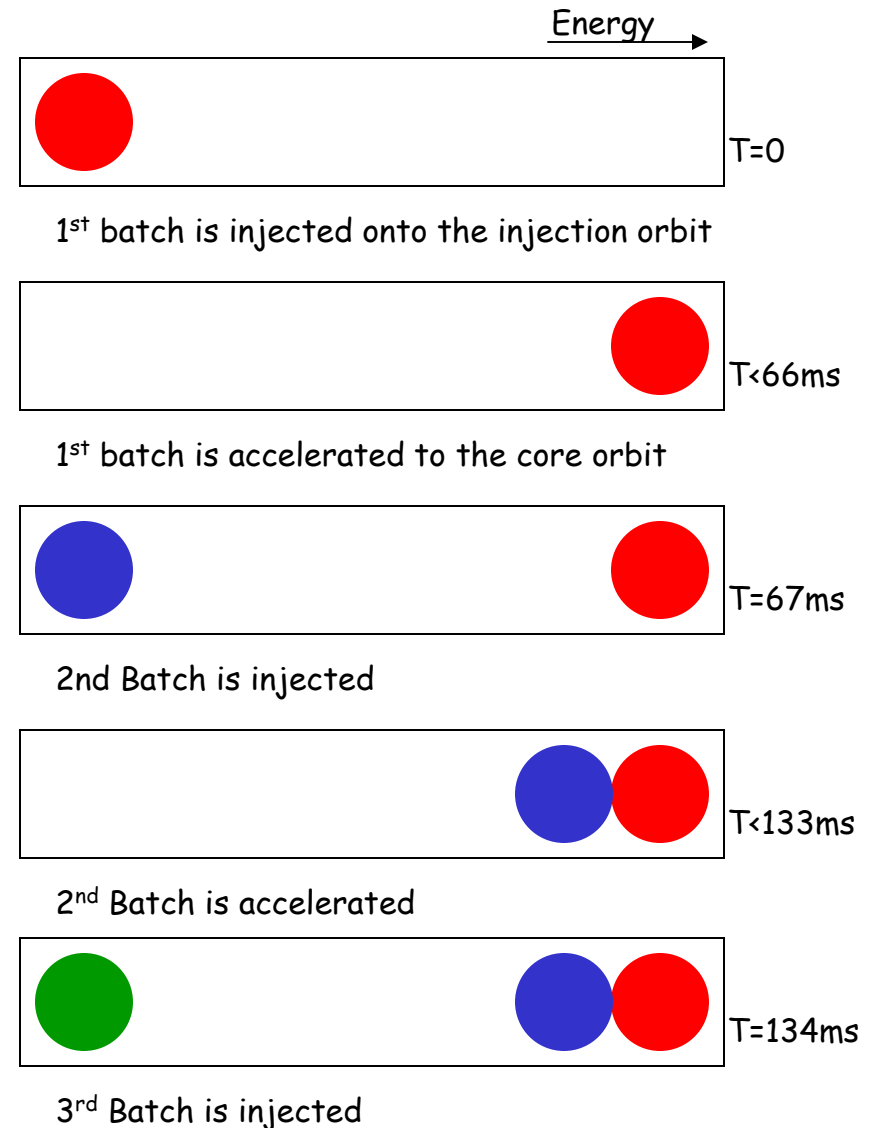
Multi-stage Proton Accumulator Scheme

- Momentum stack in the Accumulator
 - Inject in a newly accelerated Booster batch every 67 mS onto the high momentum orbit of the Accumulator
 - Decelerate new batch towards core orbit and merge with existing beam
 - Momentum stack 3-4 Booster batches
 - Extract a single Accumulator batch
 - Every 200 - 270 mS
 - At an intensity of 3-4x a single Booster batch
- Box Car Stack in the Recycler
 - Load in a new Accumulator batch every 200-270mS
 - Place six Accumulator batches sequentially around the Recycler
- Load the Main Injector in a single turn



Mechanics of Momentum Stacking

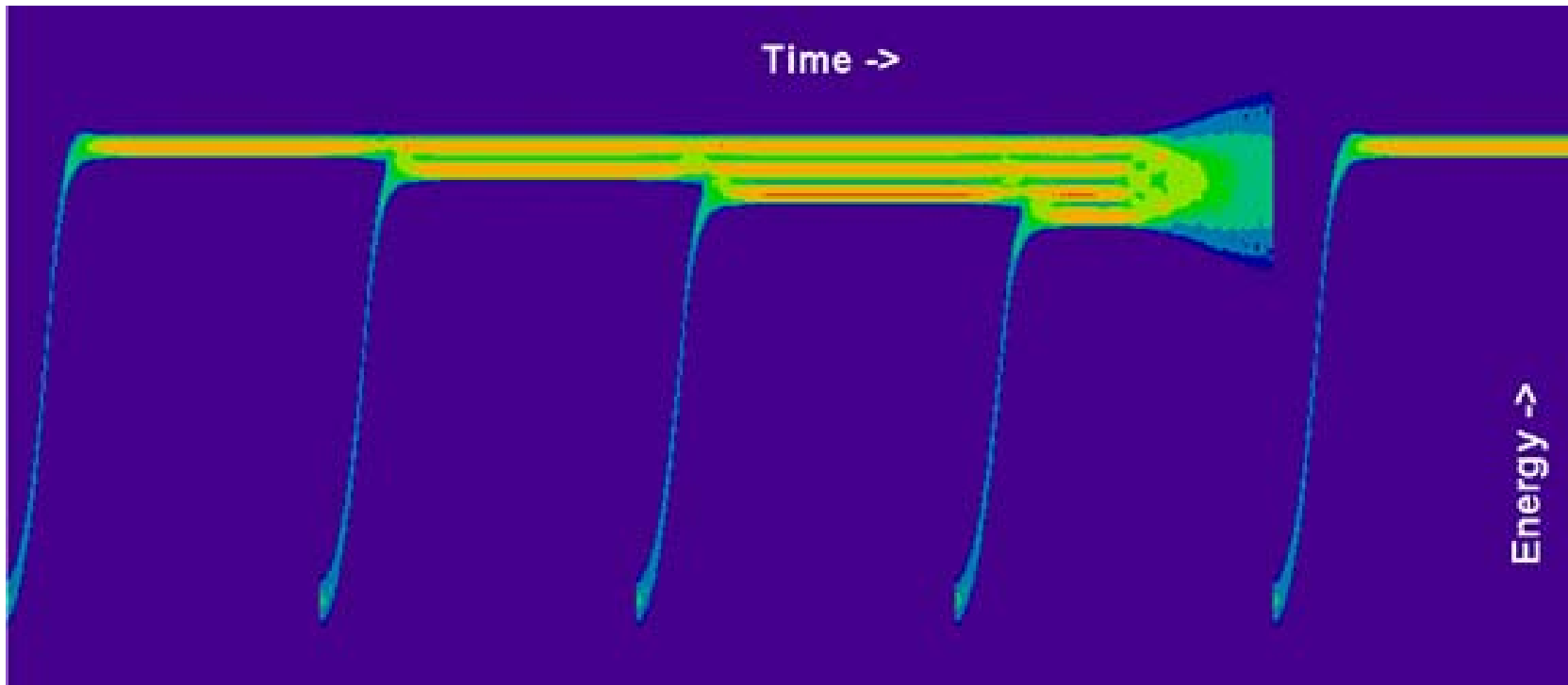
- The Accumulator was designed for momentum stacking
 - Large momentum aperture ~ 84×2.8 eV-Sec
 - Injection kickers are located in 9m of dispersion
 - Injection kickers do not affect core beam
- Inject in a newly accelerated Booster batch every 67 mS onto the low momentum orbit of the Accumulator
- The freshly injected batch is accelerated towards the core orbit where it is merged and debunched into the core orbit
- Momentum stack 3-4 Booster batches





Momentum Stacking

Output longitudinal emittance = $84 * 0.38 \text{ eV-sec}$

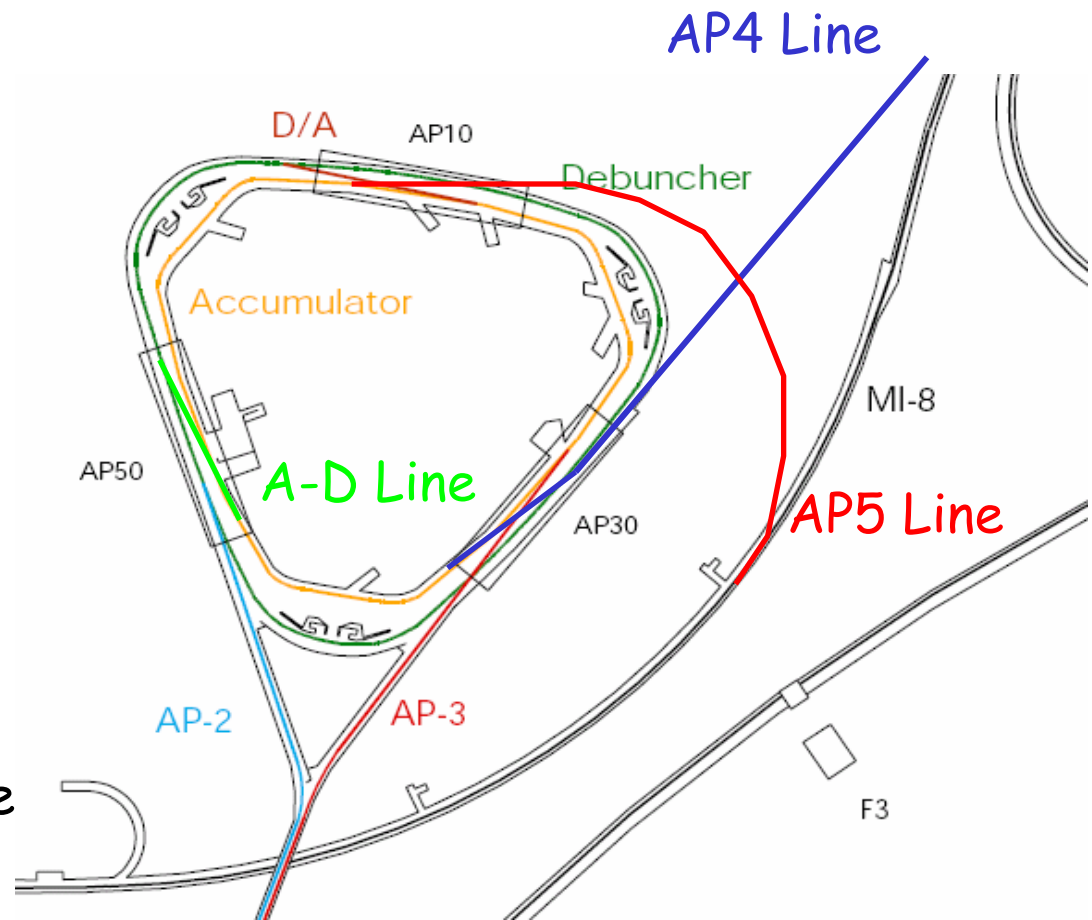


Input longitudinal emittance = $84 * 0.08 \text{ eV-sec}$



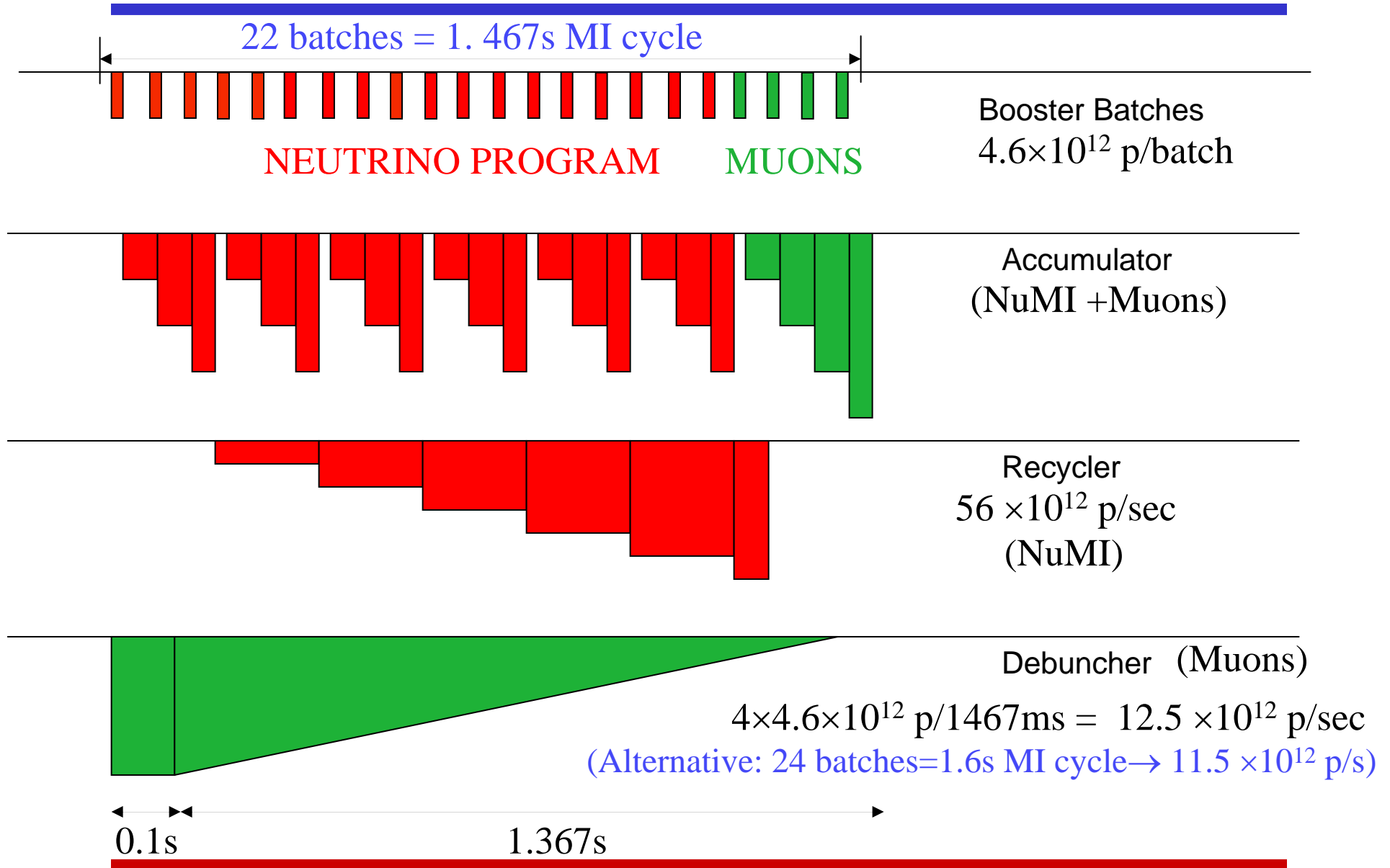
New Transfer Lines to the Antiproton Source

- After acceleration in the Booster, the beam will be transferred DIRECTLY to the Accumulator ring
- The Booster is connected to the Accumulator via a new AP4 Line
- The line comes in A30 underneath the Debuncher. The Accumulator is connected to MI-8 line for SNUMI injection via the new AP5 Line





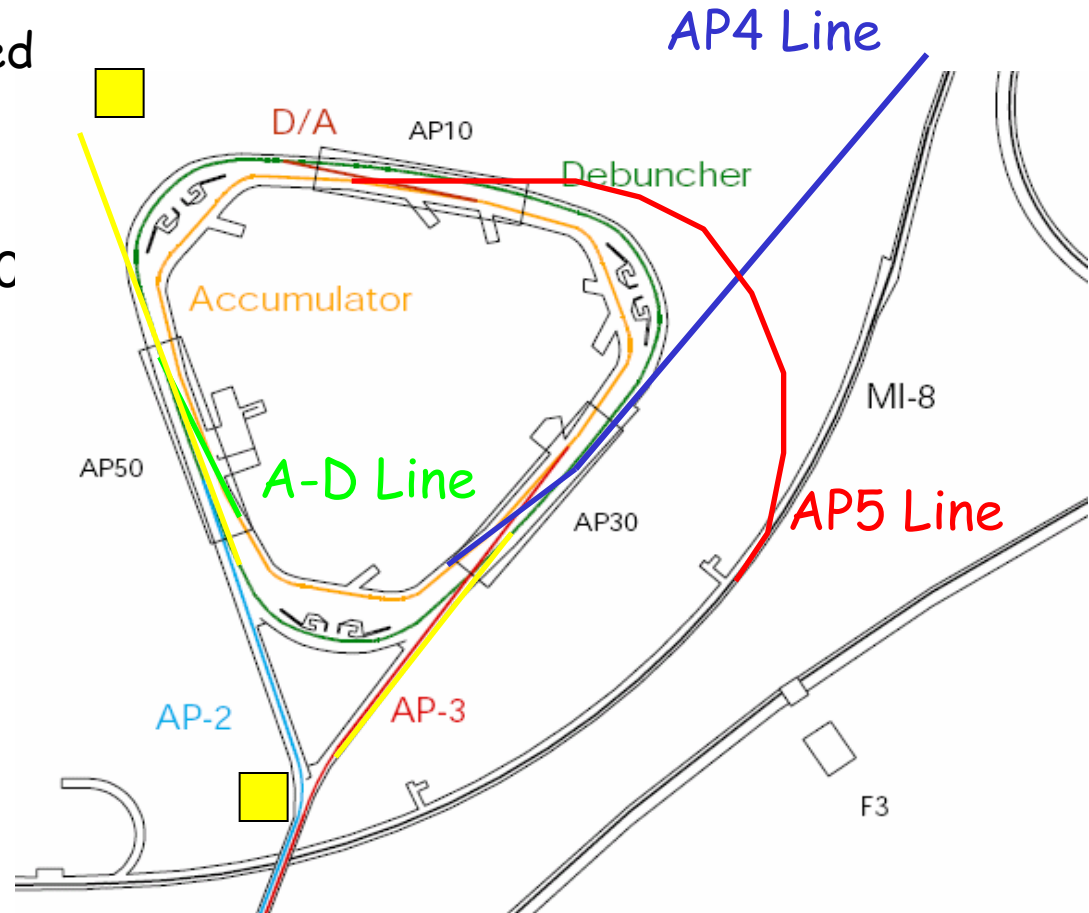
Mu2e and SNUMI





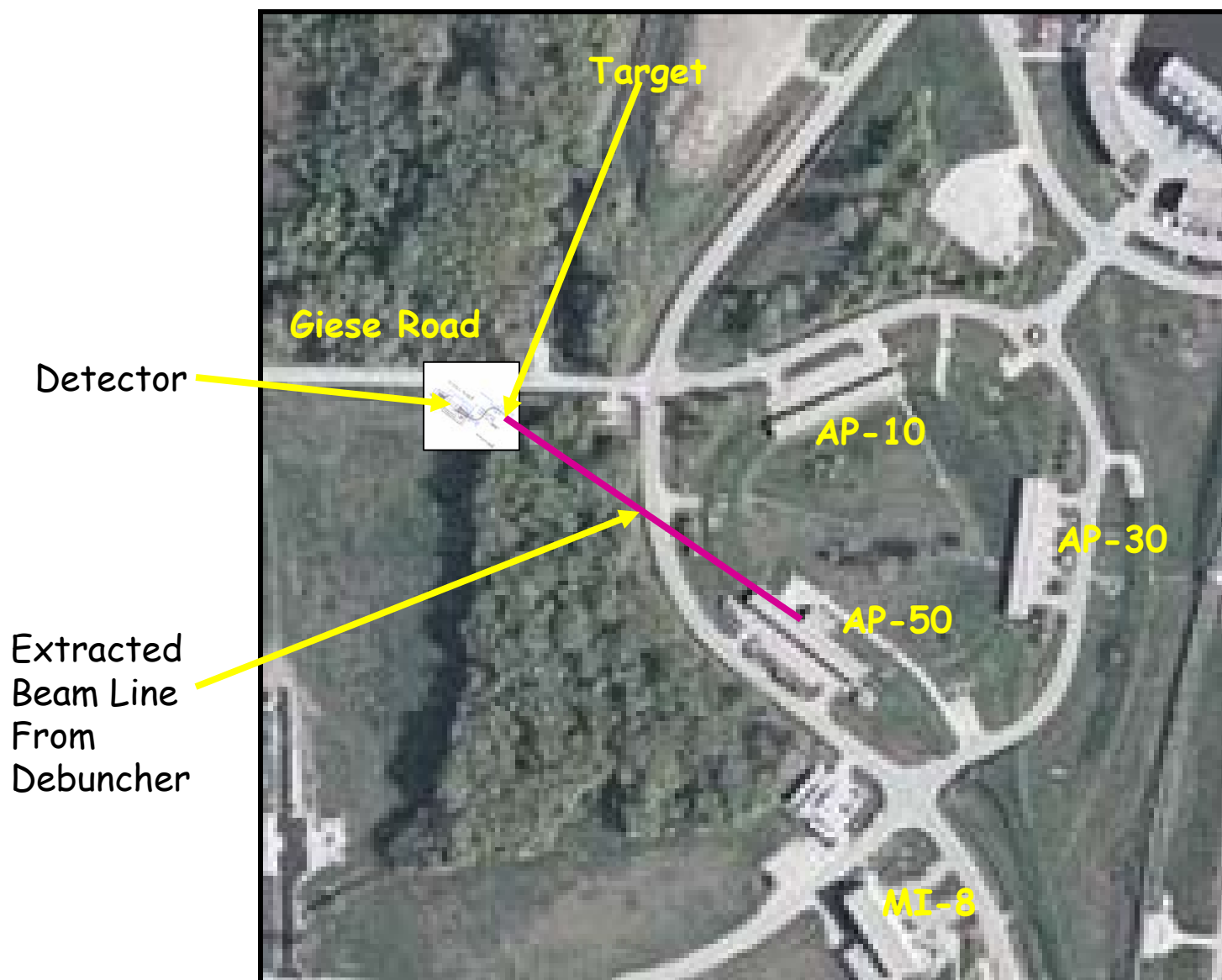
μ -to-e Extraction Line

- The Accumulator is connected to the Debuncher for μ -to-e injection via the reversed D-A line (A-D line)
- The beam is slow spilled extracted from the Debuncher at either D30 or D50
- At D30, the extracted beam goes towards AP3
- At D350, the extracted beam heads west





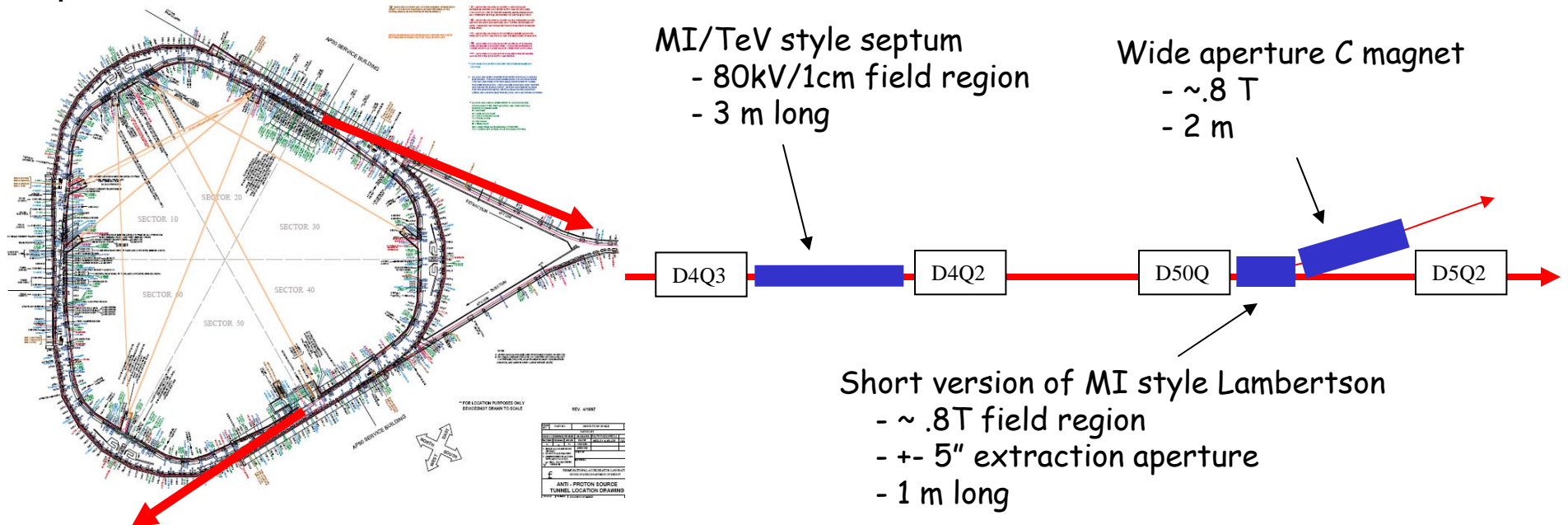
Location of Mu2E target and Detector





Resonant Slow Extraction

options:

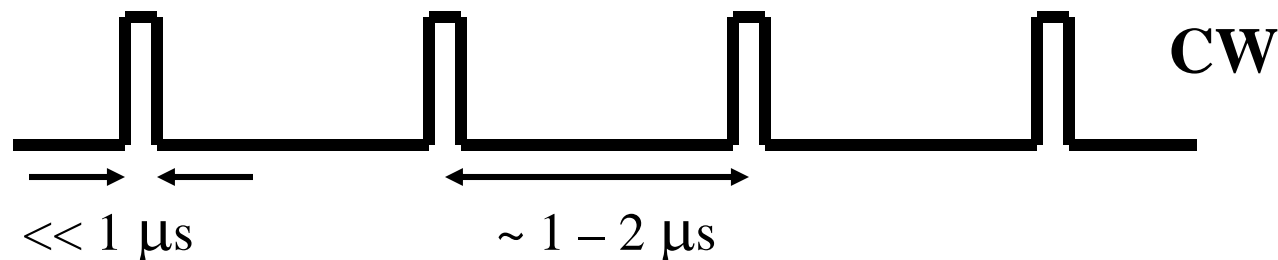


- Extraction scheme appears workable
- Studying details of resonance generation
 - Also comparing 2nd integer vs. 3rd integer
- Extraction loss a worry
 - ~ 500 W loss with typical (2-3%) resonant extraction inefficiencies
 - Must be considered from the beginning in the design



Beam Requirements

- To reach MECO goal: Requires $\sim 10^{20}$ primary 8 GeV protons per year with the right bunch structure.
- Bunch lengths short compared to the lifetime of muons orbiting a nucleus (1.1 ms for Al)
 - with a bunch spacing longer than this time
 - but not too much longer since we want to minimize peak rates.
- Experimental signature:
 - mono-energetic electron & nothing else.
 - To minimize backgrounds, when there is no incoming primary beam there must be no beam at the level of 1 part in 10^9 .
- Ideal Bunch Structure for the slow muons (& for the primary protons)





Proton Beam Specification

Example: 4.6×10^{12} protons per Booster Batch & a 1.467s MI cycle

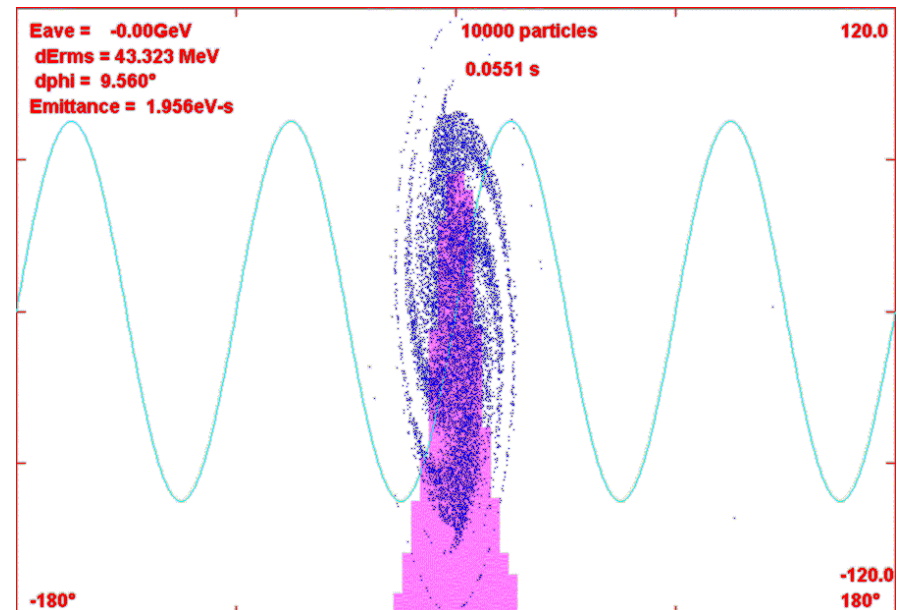
Beam Energy	8 GeV
Bunch Trains / sec: f_{TRAIN}	0.682
Bunch Spacing: ΔT_B	1.6 μs
No. of bunches/train: N_B	85×10^4
No. protons/bunch: n_p	2.16×10^7
Bunch Length (2.5s) : t_B	150 ns ($s=60\text{ns}$)
Protons/train (4 batches)	1.84×10^{13}
Protons/year (10^7 secs)	1.25×10^{20}

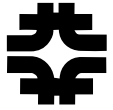
Four years running $\rightarrow 5 \times 10^{20}$ protons $\rightarrow 1.3 \times 10^{18}$ stopped muons



Beam Bunching for mu2e

- Bunch beam to a fraction of the Debuncher circumference
 - $< \sim 200\text{ns}$ of 1700ns
- Keep beam leakage outside that bunch length to a minimum
- Debuncher timings are similar to MECO/BNL
- Develop most effective/efficient bunching scheme
 - barrier bucket
 - Multi-harmonic
- Will need a fast kicker in the Debuncher ring to further clean gap.
- Multi-harmonic example
 - rf multi-harmonic buncher
 - Example: $h=1$, $V_{\text{rf}}=30\text{kV}$; $h=2$, $V_{\text{rf}}=15\text{kV}$; $h=3$, $V_{\text{rf}}=10\text{kV}$
 - $h=4$: $7.5 \rightarrow 50\text{kV}$ (to hold compressed beam)
 - 0.055s for bunching





Multi-stage Proton Accumulator Issues

- Once the SNUMI group provides a conceptual design report for slip-stacking in the Recycler, it will begin to further develop the concept of momentum stacking in the Accumulator.
- List of Issues
 - Momentum Stacking
 - Booster throughput
 - Transfer line design
 - Space charge effects in the Accumulator and Recycler
 - Radiation shielding
 - Beam-loading
 - Transition crossing in the Main Injector
 - Instabilities (electron cloud, coupled bunch, etc.)
 - Mu2e Accelerator Issues
 - Slow Spill system in the Debuncher
 - Beam loss in the Debuncher
 - Extinction of unwanted particles in bunch gap
 - Fast Kicker design for beam cleaning
 - Dump design for beam cleaning
 - Transfer line design to experiment



Summary

- Momentum stacking has much smaller longitudinal emittance dilution than slip stacking and can be used in place of slip stacking to achieve proton fluxes much greater than 14×10^{16} /hour
- Because the Accumulator was designed for momentum stacking, the present antiproton production complex can be converted into a multi-stage proton accumulator
 - Accumulator -> Momentum Stacker
 - Recycler -> Box Car Stacker
 - Debuncher -> Slow Spill to mu2e
- The multi-stage proton accumulator can supply enough protons for a 1.1 MW 120 GeV beam and 1×10^{20} 8 GeV protons / year for mu2e.